ROTATIONAL MIXING AND THE PRIMORDIAL LITHIUM ABUNDANCE

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Abstract.

There has been recent progress in the study of the angular momentum evolution of low mass stars (Krishnamurthi et al 1997a). Theoretical models can now be constructed which reproduce the angular momentum evolution of low mass open cluster stars and the distribution of initial conditions can be inferred from young clusters. In this poster we report on the application of these models to the problem of rotational mixing in halo stars.

The distribution of initial conditions inferred from young clusters produces a well-defined halo lithium "plateau" with modest scatter and a small population of outliers. Different choices for the solar calibration produce a range of absolute depletion factors. We show that both the dispersion and the ratio of ^{6}Li depletion to ^{7}Li depletion increase as the absolute ^{7}Li depletion increases. The measured ^{6}Li in HD 84937 and the dispersion in the plateau set independent upper bounds on the ^{7}Li depletion. Consistency with open clusters and the Sun, along with claims of an intrinsic dispersion in the plateau, set a lower bound. We derive a range of 0.2-0.4 dex ^{7}Li depletion in halo field stars. Implications for cosmology are discussed.

1. Introduction : Rotational Mixing and Lithium

- ^{7}Li is important as a test of Big Bang nucleosynthesis (Boesgaard & Steigman 1985). Current estimates of the primordial ^{4}He favor low baryon densities, while conflicting estimates of the primordial deuterium abundance are consistent either with low or high baryon densities. ^{7}Li may enable us to distinguish between these options.
- Lithium is destroyed at relatively low temperatures in stellar interiors (of order 2.5×10^6 K). Surface lithium abundances can therefore be affected by nuclear burning (if the surface convection zone is sufficiently deep), mass loss, microscopic diffusion, and mixing.

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- The lithium depletion pattern seen in open clusters is not consistent with the predictions of standard stellar models (see Pinsonneault 1997 for a review.)

- Although the agreement between standard models and halo stars is better, implying a low primordial ^{7}Li, the ^{7}Li abundances of halo stars may have been affected by the same process affecting open clusters.

- Rotational mixing is an attractive explanation for this overall pattern. The time dependence of lithium depletion in models with rotational mixing matches the data (Chaboyer et al. 1995a,b). Models with different initial rotation rates experience different degrees of mixing, providing a natural explanation for a dispersion at fixed T_{eff} (Pinsonneault et al. 1989).

- In this poster we examine the distribution of lithium depletion factors expected from the observed distribution of initial conditions seen in young cluster stars. We show that the slope of the Li-T_{eff} relationship is consistent with rotational models and use the halo star dispersion and the ratio of ^{6}Li to ^{7}Li depletion in HD 84937 to place limits on the primordial ^{7}Li.

2. Rotational Properties of the Models

Internal angular momentum transport from hydrodynamic mechanisms, and the associated mixing, is included in the models (Krishnamurthi et al 1997a).

The initial conditions are generated by assuming that accretion disks enforce a rotation period of 10 days in the surface convection zone of a T Tauri star until they decouple from the central star. A range of disk lifetimes is used to generate a range of rotation rates on the main sequence. The distribution of disk lifetimes needed to reproduce the observed rotation rates in young open clusters is strongly peaked, with a majority of slow rotators and a small population of fast-spinning stars (Krishnamurthi et al. 1997a).

Rotational mixing is calibrated by requiring that for some value of the solar accretion disk lifetime a solar model have the solar ^{7}Li abundance at the age of the Sun. We chose three different initial conditions (0, 0.3, and 1 Myr disk lifetimes) for the Sun. The no disk case corresponds to the assumption that the Sun was a rapid rotator in its youth (and thus will experience more lithium depletion than typical for stars of its mass and age). The 1 Myr disk case would make the Sun a slow rotator, which would imply that the solar lithium depletion was typical of its mass and age.

An angular momentum loss law which saturates at high rotation rates is used; the observational data requires a saturation threshold that depends on the convective overturn time scale (Patten & Simon 1996, Krishnamurthi et al. 1997b).

3. Lithium Depletion in Open Cluster Stars

In previous work, rotational mixing from a wide range of initial angular momenta has been considered. In this poster, we use the observed distribution of rotation

rates in young open cluster stars to infer a distribution of initial conditions. We then examine the distribution of lithium abundances that would be seen in open cluster stars of different age as follows :

- Models with the [Fe/H] and ages of the clusters were constructed. For the T_{eff} of each cluster star with lithium data, a disk lifetime was chosen at random from the Pleiades distribution of initial conditions. We looked at two different solar calibrations. In Figure 1 simulated lithium depletion patterns for open cluster stars are shown for the models where the Sun is at the birthline.

  In Figure 2 we show simulated lithium depletion patterns for open cluster stars for a model where the Sun is a typical star with a 1 Myr disk.

- There is minimal rotational mixing in young stars.

- A narrow band of depletion factors for the majority of open cluster stars is produced by the slow rotators in the Pleiades distribution of initial conditions.

- Rapid rotators have different properties. The wide range in lithium depletion seen in young cool stars is not produced by early rotational mixing even in rapid rotators. Rapid rotators also develop excess lithium depletion on the main sequence relative to slow rotators.

- This relative pattern implies that if the fraction of rapid rotators varies from system to system the magnitude of the dispersion could also be different in different systems. For example, the large dispersion in globular cluster main sequence stars relative to field halo stars (Boesgaard et al. 1997 [B-100] and Thorburn et al. 1997 [B-112]) can be naturally explained in the rotational mixing framework by a different distribution of initial conditions.

4. Dependence of Lithium Depletion on the Solar Calibration; Halo Lithium Abundances

Simulated distributions of halo lithium abundances for the three solar calibrations are shown in Figure 3. As the degree of mixing increases, both the mean depletion and dispersion increase.

A nearly flat plateau, with little scatter, is expected for the distribution of initial conditions seen in young clusters. The curvature in the Li-T_{eff} plane present in earlier models of rotational mixing is absent because of the mass dependence of the angular momentum loss law.

The detection of ^{6}Li has been claimed in one hot halo star (HD 84937). Slow mixing allows simultaneous depletion of ^{6}Li and ^{7}Li while preserving detectable amounts of both. The ratio of ^{6}Li to ^{7}Li depletion ratio increases with increased ^{7}Li depletion. The dispersion and ^{6}Li/^{7}Li depletion ratio can therefore both be used as diagnostics of the degree of ^{7}Li depletion in halo stars.

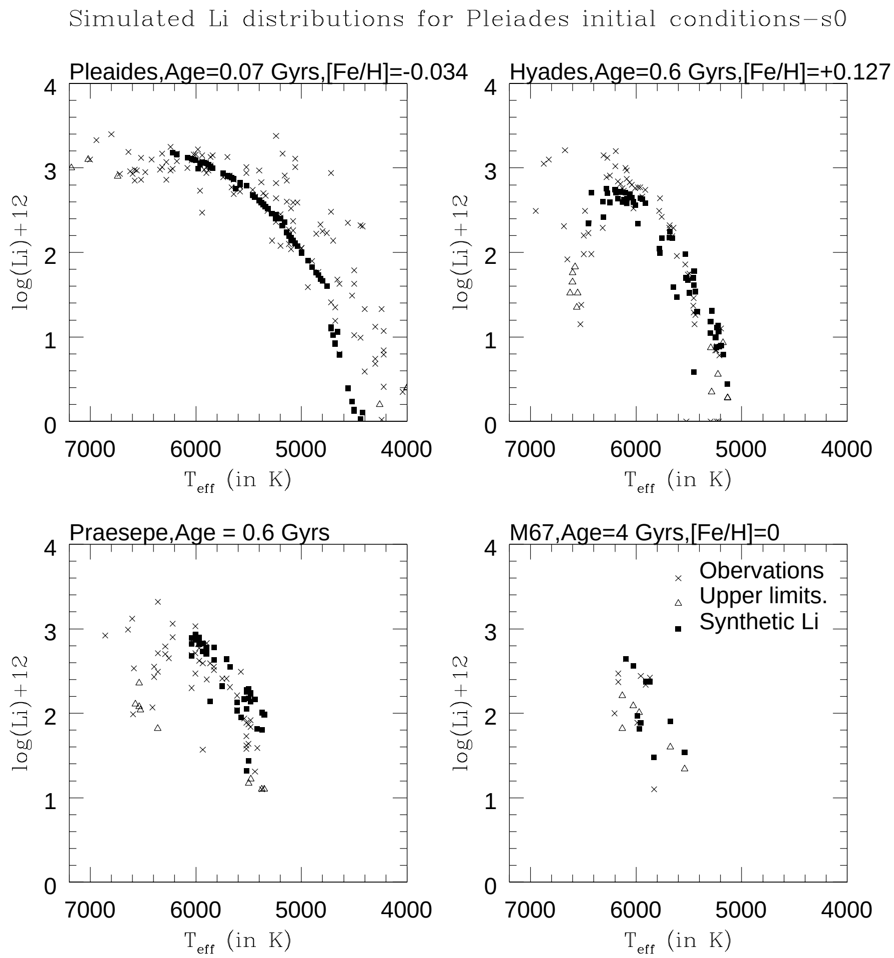

Figure 1. Simulated distributions of ^{7}Li abundances in open clusters compared with data (Soderblom et al. 1993, Deliyannis et al. 1994, Balachandran 1995). For each data point, the initial condition was randomly drawn from the Pleiades distribution of initial conditions. A lithium depletion appropriate for that initial condition was then applied to an assumed initial abundance log N(Li) of 3.4 (young systems) or 3.3 (M67 and the Sun) on the scale where log N(H) = 12. The models in this figure used a solar calibration in which the Sun was assumed to have a 0 Myr disk lifetime; this represents the minimum mixing and dispersion case.

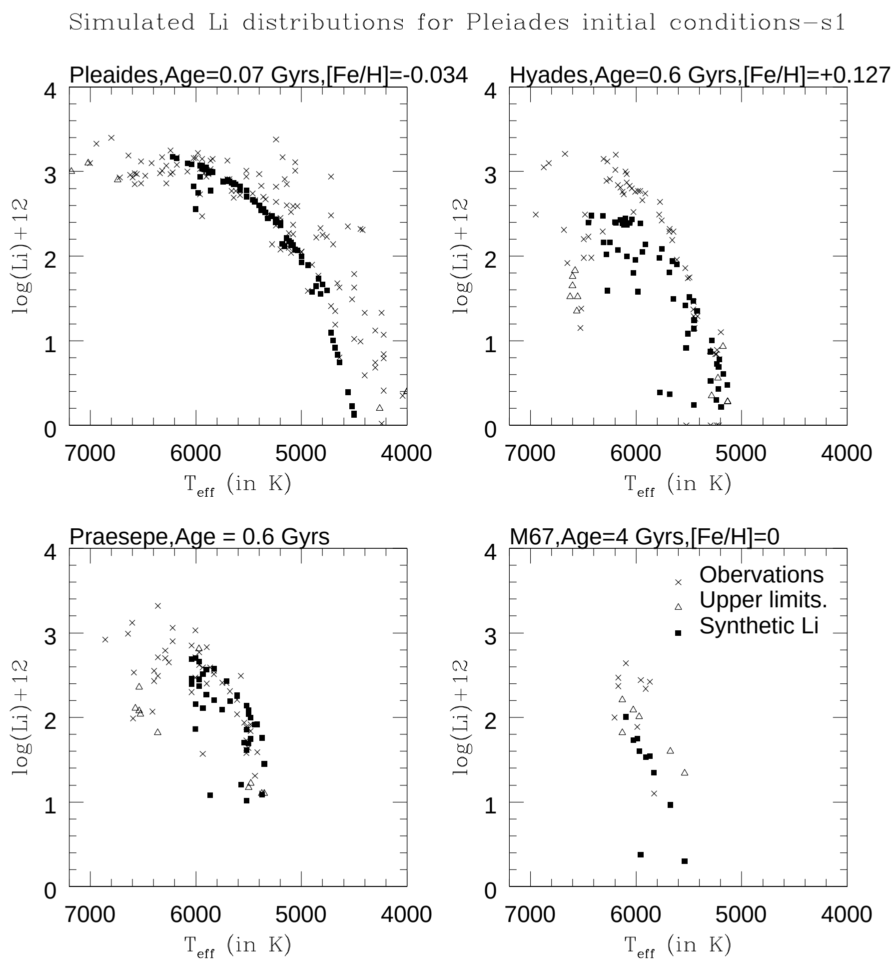

Figure 2. The same as Figure 1, except that the models in this figure used a solar calibration in which the Sun has a 1 Myr disk; this represents a large mixing and dispersion case.

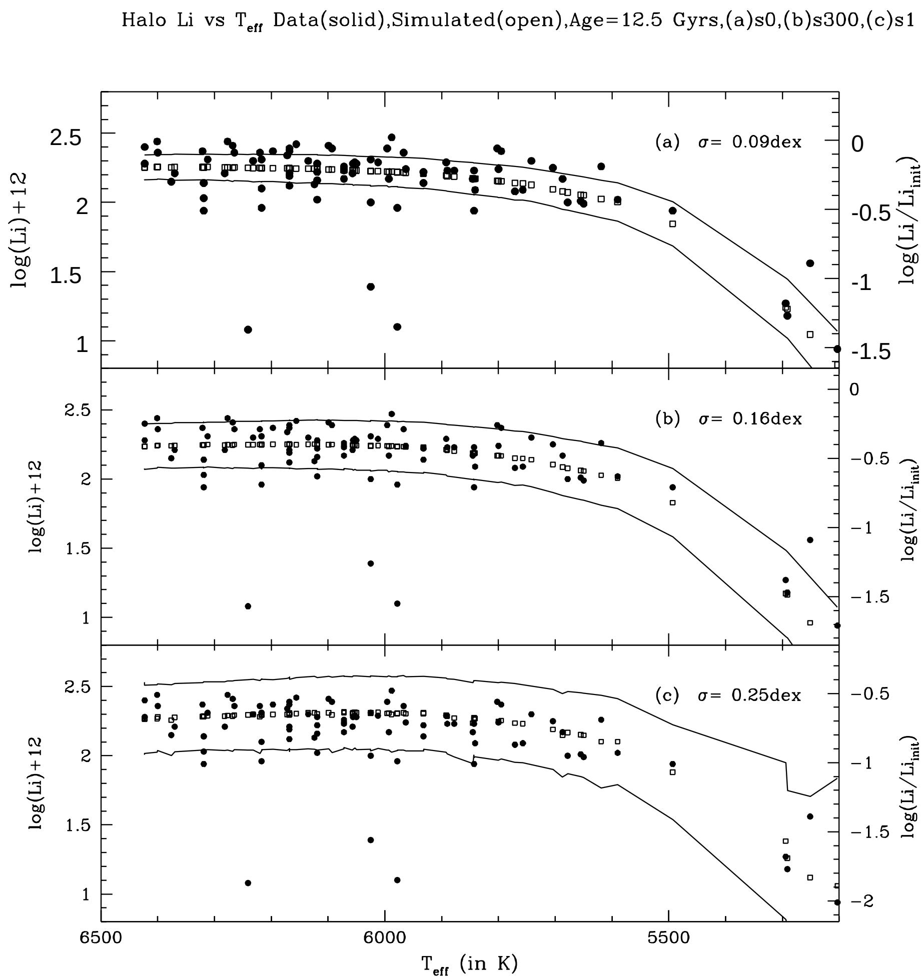

Figure 3. Lithium abundances for halo stars (data from Thorburn 1995) are compared with simulations for three different solar calibrations. The open symbols are the mean depletion values for each data point in the simulation and the solid lines are displaced +/- 1 σ from the mean trend in the models. In panel a, the calibration with the 0 Myr disk coupling time scale for the Sun is used; a primordial ^{7}Li abundance log N(Li)$_p$ = 2.5 is inferred. In panel b, the calibration with the 0.3 Myr disk coupling time scale for the Sun is used; log N(Li)$_p$ of 2.7 is inferred. In panel c, the calibration with the 1 Myr disk coupling time scale for the Sun is used; log N(Li)$_p$ of 3.1 is inferred.

5. Bounds on the Primordial ^{7}Li Abundance

The dispersion in the data of Thorburn (1994) is 0.13 dex around the mean Li-T_{eff} trend and 0.16 dex when defined in the same way as in the models. Observational error and a range in metallicity and age will compose some of this dispersion, implying that the dispersion which can be attributed to rotational mixing will be smaller than 0.16 dex. The dispersion in the halo plateau therefore sets an upper bound on the ^{7}Li depletion in halo plateau stars of 0.4 dex.

There is a claimed detection of ^{6}Li in one halo star, HD 84937. A bound on the initial ^{7}Li in this star can be made from the ^{6}Li/^{7}Li ratio if a maximum initial ^{6}Li abundance can be established. ^{6}Li is produced by spallation, either from CNO nuclei or from $\alpha - \alpha$ fusion synthesis. Stringent limits of 0.6 dex ^{6}Li depletion have been claimed based on CNO spallation (Lemoine et al. 1997). However, the observed level of ^{6}Li is higher than the predicted level even before possible depletion is taken into account. If $\alpha - \alpha$ fusion synthesis is included we can set a firm limit on the ^{6}Li depletion of 1.3 dex, corresponding to an initial ^{6}Li for HD 84937 equal to the solar meteoritic value. A limit of 0.55 dex ^{7}Li depletion can be placed based on the ^{6}Li constraint. This limit is less stringent than the limit based on the dispersion.

Consistency with the open cluster data, the inferred intrinsic dispersion in the plateau, and the existence of highly overdepleted halo stars all act to bound the ^{7}Li depletion from below. The lower bound on the ^{7}Li depletion is 0.2 dex.

6. Cosmological Implications

An initial abundance of 2.25 ± 0.1 and a depletion of $0.2 - 0.4$ dex produces a predicted range $2.35 < \log \mathrm{N(Li)}_p < 2.75$, or

$2.2 < 10^{10}(Li/H) < 5.6$.

There are two ranges of the baryon to photon ratio η consistent with the above limits on $\log \mathrm{N(Li)}_p$: a "low η" branch with $0.8 < \eta_{10} < 1.7$ and a "high η" branch with $3.7 < \eta_{10} < 9.0$ ($\eta_{10} = \eta$ in units of 10^{-10})

The inferred $\log \mathrm{N(Li)}_p$ is in good agreement with the η implied by low deuterium abundances in QSOs (Tytler et al. 1996) for the high η branch. This implies

$0.014 < \Omega_b h^2 < 0.033$.

The inferred $\log \mathrm{N(Li)}_p$ is in good agreement with the η inferred from ^{4}He (Olive et al. 1997) for the low η branch and consistent with the high deuterium abundances claimed for some QSOs (Rugers & Hogan 1996). The baryon density corresponding to this branch is low,

$0.003 < \Omega_b h^2 < 0.006$.

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